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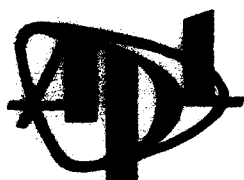
**Acoustic Thermometry of Ocean Climate (ATOC):
Selection of California Source Site**

by Bruce M. Howe

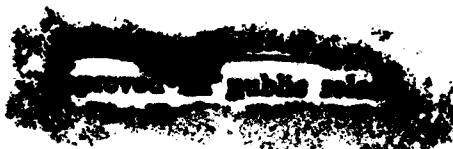
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Technical Memorandum
APL-UW TM30-93
November 1993

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1013 NE 40th Street Seattle, Washington 98105-6698



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Acknowledgments

Many colleagues contributed to the discussions leading to this report. I would especially like to thank Matt Dzieciuch for providing sound speed profiles and mode functions, and George Dworski for providing Figure 2. Nich Lesnikowski of Williamson and Associates Inc. first brought Pioneer Seamount to our attention as a possible source site. Seafloor Surveys International Inc. performed the survey work.

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ABSTRACT

This report discusses the general criteria for choosing a site for ATOC cabled sources. In particular, the process of selecting the California site is reviewed. Two possible locations are considered, Pioneer Seamount and Sur Ridge. The Sur Ridge site has been selected because a requisite marine mammal research program can be conducted there for less cost.

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1. INTRODUCTION

The goal of the Acoustic Thermometry of Ocean Climate (ATOC) program is to measure directly global ocean temperature trends in order to advance our understanding of short-term and long-term ocean variability and its relation to climate changes. The ATOC approach, which uses underwater sound signals to measure ocean temperature, is based on the fact that the speed of sound, and hence the travel time of propagating acoustic energy, is proportional to temperature.

ATOC plans to transmit signals from acoustic transmitters to acoustic receivers installed worldwide. Signal power and precise timing requirements make cabled-to-shore transmitters desirable. Mooring considerations make bottom installation preferable.

Given these factors, how is a suitable site chosen? In this report we describe the selection of one particular site off the coast of California. In so doing we also describe the criteria that must be considered for virtually all sites.

The installation of acoustic sources is the most expensive item in the program budget, and the sources will be one of the main legacies of ATOC. It is probable that other uses for the sources will become apparent, as has happened with GPS, so it behooves us to consider these decisions carefully; they will be with us for many years. In this vein, it is useful to state some of the ATOC goals:

1. measure the seasonal signal over gyre/basin scales
2. measure gyre-scale variability
3. understand the acoustics (to some extent a prerequisite to 1 and 2)
4. establish a demonstration monitoring system in the Pacific Ocean
5. design a global network
6. determine the effect of transmissions on marine mammals.

The long-term goals of ATCC are twofold:

1. establish a global acoustic network to monitor ocean climate change over long periods
2. interpret the acoustic data together with other complementary data in the framework of data-assimilating ocean models.

Other goals (in no particular order) include transmitting good signals for tomography drifters and towed arrays, providing the equivalent of underwater GPS for RAFOS floats and AUVs, establishing acoustic observatories for general research, and obtaining reciprocal transmission paths for determining absolute water velocity.

There will undoubtedly be compromises between scientific desires, technical feasibility, and cost.

Section 2 discusses general criteria and considerations, and Section 3 addresses the specifics of the California site selection process. The latter includes discussions of the local acoustics, engineering aspects (including side-scan sonar survey results), and other factors, most notably the marine mammal issue.

2. GENERAL CRITERIA AND CONSIDERATIONS

Acoustic Criteria

The primary goal in selecting a source site is to maximize the amount of nonbottom interacting acoustic energy entering the sound channel over as large an azimuthal and vertical aperture as possible. This goal dictates the following:

- The source should be at the sound channel axis so as to ensonify the entire channel.
- Over a large azimuthal aperture, bottom slopes should be large to maximize nonbottom-interacting energy and minimize bottom-interacting energy.

Ideally, the source would be at axial depth on a mooring in deep water far removed from bathymetric effects. At present, this is not feasible from an engineering standpoint (because of weight and power). Intuitively, the next best alternative would be to place the source on the peak of a seamount, with the top just at the sound speed axis. Unfortunately, a seamount is not a cone with a sharp peak; it will most likely be rounded. Thus it may not be possible to obtain a 360° azimuthal aperture, but the source could be placed to one side of the top and still utilize the steep slopes.

Azimuthal aperture is important because it defines how large a geographical area can be ensonified. Steep slopes, whether on a seamount or a tilted plane, are required to obtain clean, downward-going energy over large azimuthal apertures. Steep, tilted planes are typically associated with ocean trenches and sides of islands. How steep a slope is desired? Suppose we want a minimum vertical aperture of 12° (slope $s = 0.21$) over an azimuthal aperture of 120°; this requires a nominal slope of 23° ($s = 0.42$), which is quite steep but does occur on seamounts and sides of trenches.

Bottom interaction is undesirable for two reasons: Useful energy for sampling different parts of the ocean is lost, and bottom-interacting energy may contaminate arrivals. Spiesberger's Hawaii-to-California measurements are an extreme example of the latter (Spiesberger et al., 1992). Our experience in Bermuda (ATE90) on steep slopes (16°) with a source at 950 m, 300 m above the axis, is encouraging; no obvious problems existed with bottom-mounted off-axial receivers and an axial towed array (ATE90, 1991; Walter et al., 1993). At most sites (e.g., off California), upward-going energy can be expected to clear the bottom at its first lower turning point. Therefore the reason for wanting steep slopes is to obtain all the downward-going energy and have it and the upward-going energy free from bottom interaction.

It can be argued that the downward-going energy is redundant as long as the positive-launch-angle rays are resolved at the receiver. The downward-going energy will reduce the error in the range-averaged profile by at best \sqrt{N} , where N is the number of

rays. First-order oceanographic results should be obtainable from only the positive-launch angle rays. My counterargument is that the down-going rays are desirable *because* they are redundant. If some bottom-interacting energy is present in the arrival pattern, the chances are greater that a clean ray identification can be made and followed over time with more distinct ray arrivals than with fewer.

I leave the theoretical arguments of near-source, ray and/or mode bottom interaction to others (Munk, 1993; Chiu, 1993) and use the simple-minded ray paradigm.

A crude measure of the area ensonified by a source can be obtained from shadow plots. The present version of these plots simply follows a depth surface defined as the sound channel axis depth (or deeper) on radial geodesic lines from the source location until bathymetry is struck; beyond that point is an acoustic "shadow." An example is given in Figure 1. In the future, the surface to be followed will be that formed by the lower turning points of the rays of interest.

There are two extremes in sound speed profiles: the Arctic type with the sound speed axis at the surface, with all energy interacting with the surface; the tropical type, where the axis is deep and the surface sound speed is high, producing mostly refracted (RR) energy. It is not clear whether one is better than the other. For refracted, surface-reflected (RSR) rays, the per bounce loss is relatively small at 70 Hz and low wind speeds (see Table 1), and the variance in internal wave travel time is minimal. At long ranges, it is believed that the spread (breaking up of a single ray path into micro-multipaths) of RR rays will be large. S. Flatté has used an AMODE profile (Bermuda-Puerto Rico) with a range of 5 Mm to estimate a spread of 200–300 ms for RR ray arrivals, and theory says this should grow as range squared. Does this mean that an individual ray will be smeared out and adjacent rays will merge over long ranges? There are no data as yet to say. Spiesberger's 3000-km arrival pattern, from an axial RTE87 source to a deep receiver (Spiesberger and Metzger, 1991), appeared clean, but the arrivals were identified as RSR or RR with very shallow upper turning depths that could in fact be pure RSR. At this point, we in tomography have used only clean, early ray arrivals and the final axial cutoff. Slice89 showed that we cannot accurately predict final arrivals that are somewhat off axis. The wisest course would be to retain as much energy as possible.

Technical Feasibility and Cost

Technical feasibility and cost are intertwined. The sources will be designed for a 10-year life and will require significant amounts of power. Present engineering capability requires that the sources be bottom mounted and cabled to shore. Also, a four-element vertical hydrophone array (spacing $3/2 \lambda$ at 70 Hz) and pressure and temperature sensors will be part of the source package. Some of the general criteria follow (the order does not imply priority).

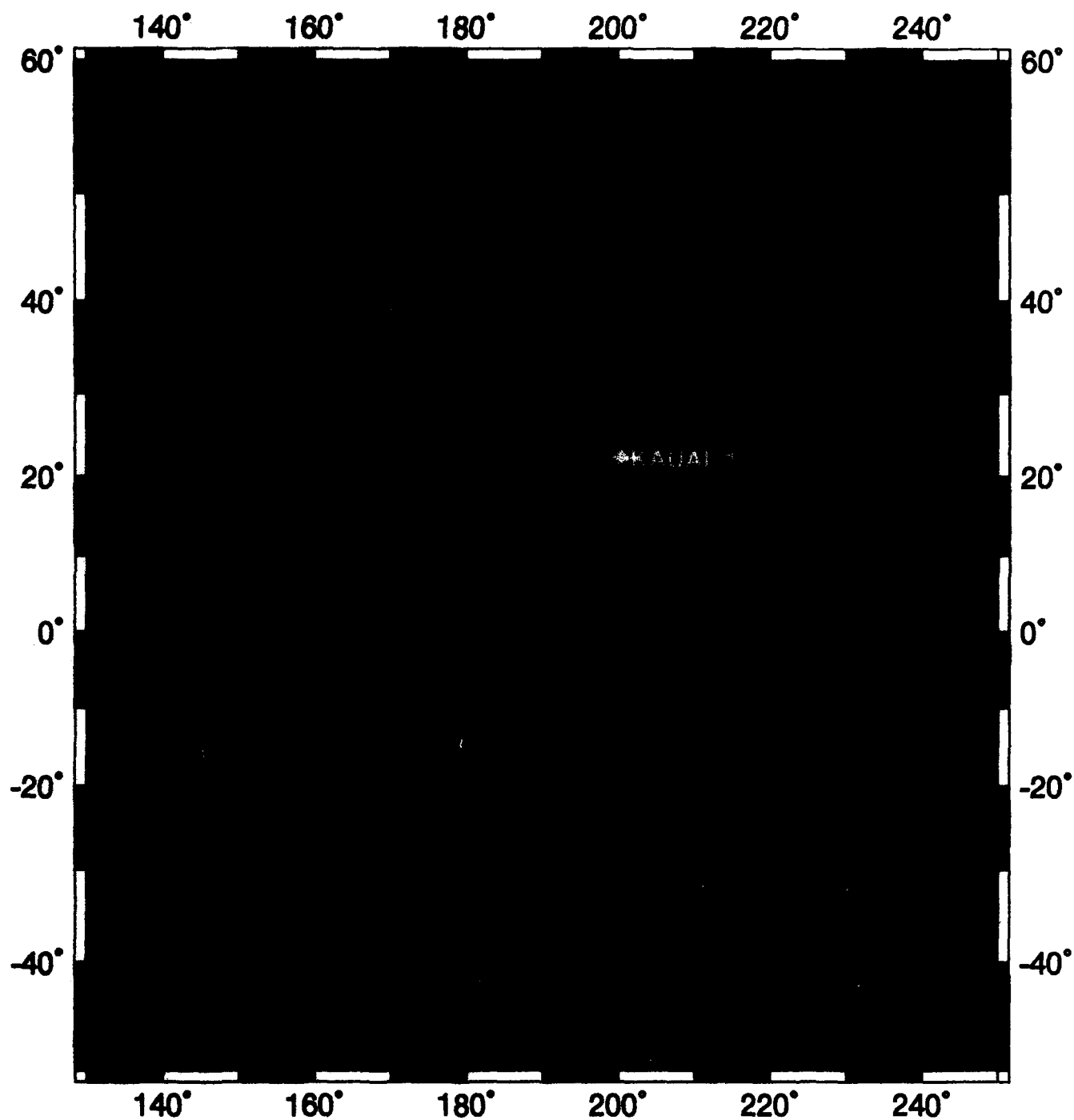


Figure 1. A "shadow" plot for the Kauai source. Depth = 1000 m.

Table 1. *Scattering loss calculations for two ray angles for a frequency of 70 Hz. The number of surface bounces is taken to be 100 in both cases. After Brekhovskikh and Lysanov, 1982.*

Surface Grazing Ray Angle θ , deg	Wind Speed, m/s	σ , m	Rayleigh Parameter P^a	Coherence, $\exp(-P^2)$	Loss per Reflection, ^b dB	Total Loss, dB
12	5	0.1	0.012	0.9998	0.00065	0.065
	10	0.57	0.070	0.995	0.021	2.09
	15	1.57	0.19	0.964	0.16	15.9
8	5	0.1	0.0081	0.9999	0.00029	0.029
	10	0.57	0.047	0.998	0.0094	0.94
	15	1.57	0.13	0.983	0.07	7.1

^a $P = 2k\sigma\sin(\theta)$, $k = 2\pi/\lambda$, and $\lambda = C / 70 \text{ Hz} = 21.4 \text{ m}$.

^bLoss per reflection = $10 \log_{10}$ (coherence).

- The length of the cable run should be as short as possible to minimize outright cost of cable and cable voltages (most cables are voltage limited).
- The bathymetry and shore termination conditions should not require extensive armoring or trenching of the cable.
- The location should be convenient for logistics, necessary permits, and shore-based power and communications.
- The source depth should be minimal to reduce weight, gas volume (of the pressure compensation system), system complexity, and cost. (This may conflict with the desire to have the source at the sound channel axis.)
- The risk of damage due to bottom fishing should be minimized.

Maps showing the intersection of the sound speed axis with bathymetry are useful to narrow down possible locations. Including the maximum possible cable distance in such a map indicates where shore sites are feasible. Such a map of the California coastline is shown in Figure 2. In future work, local bottom slope magnitudes in an acceptable depth range will be plotted as well.

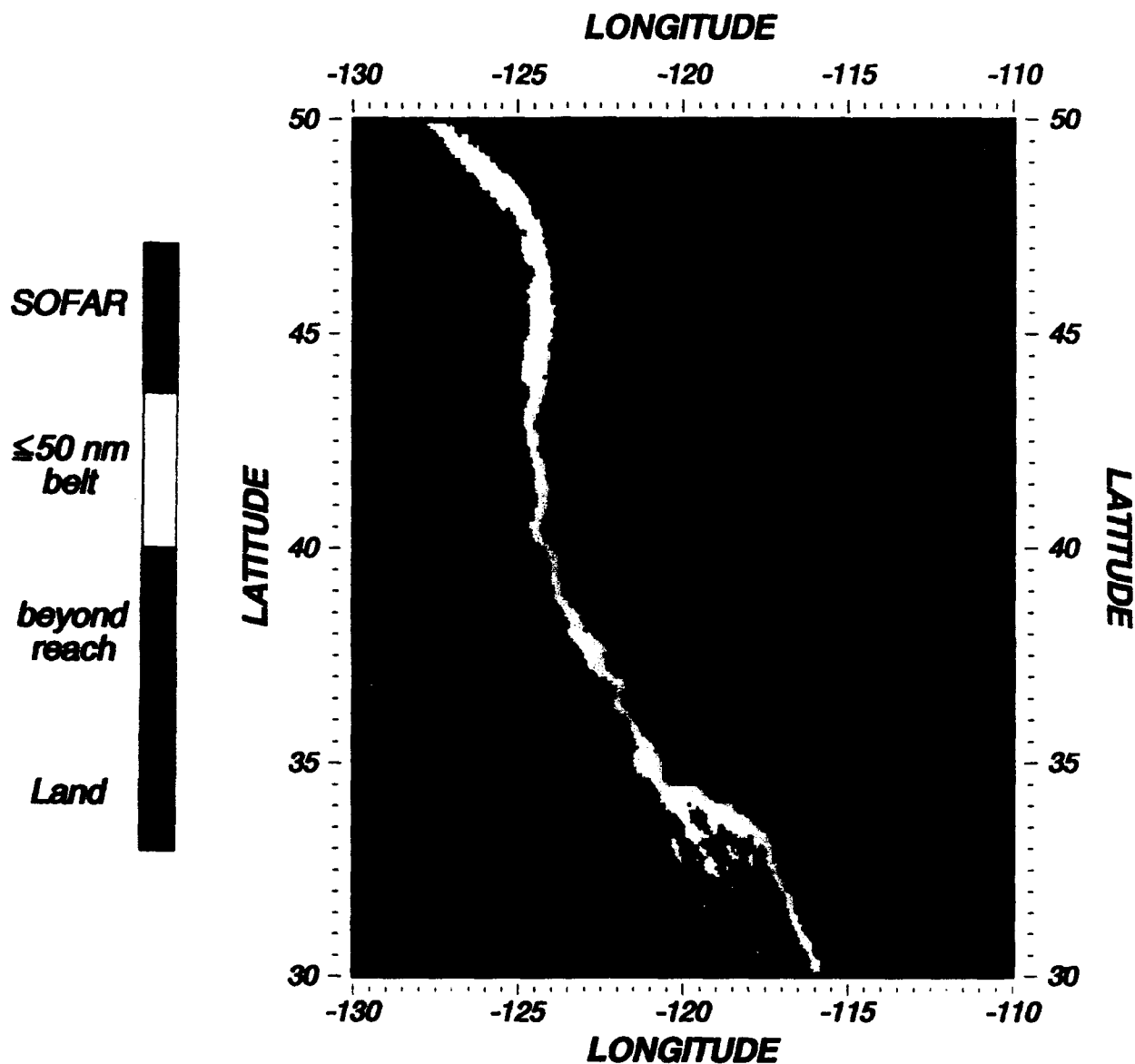


Figure 2. A map of the California coast showing the intersection of the sound speed axis with bathymetry (blue/yellow boundary). The maximum width of the yellow strip is 50 n.mi.; if yellow touches land, then the sound channel is within this distance of land. If red comes between land and the yellow area, the sound channel is unreachable with a cable 50 n.mi. long. (The morphological algorithm for this has analogues in biology (plaque in arteries) or geology (ore veins).)

Other Considerations

There is a desire to minimize any effects the source may have on nearby marine mammals. This dictates a geographical location away from areas where marine mammals live and/or placing the source deep enough that sound pressure levels at the surface are sufficiently reduced. In any event, an area where many marine mammals live and the sound channel shoals (polar regions) is not desirable because the source would need to be too close to the surface. (However, A. Bowles of the Hubbs - Sea World Research Institute has said that a source off Adak probably would not require a permit.)

Approval is required by the National Marine Fisheries Service (NMFS, part of NOAA) for any U.S.-funded work that may adversely affect marine mammals (under the aegis of the Marine Mammals Protection Act). It is not clear how the need for a permit is determined and, if one is needed, what one must do to "earn" it. More will be said about this later.

3. PARTICULARS FOR CALIFORNIA

Two sites have been proposed for a source off California, Pioneer Seamount and Sur Ridge (Figure 3). The two are compared in Table 2. Detailed bathymetry charts are shown in Figures 4 and 5. The depth at the Pioneer Seamount site is about 980 m; at the Sur Ridge site it is about 880 m.

Acoustics

The sound channel is nominally at 600 m but individual profiles show the channel is broad, extending from about 500 m to 1000 m (Figure 6). A ray trace shows that $+8^\circ$ rays graze the surface and that $+12^\circ$ rays are limited by the bottom depth (3500 m) 10 to 20 km from the source. The acoustic normal modes are well excited, with the exception of mode 1 which is down in amplitude to about 0.36 at 1000 m. Pioneer Seamount is probably as close to an ideal cone as possible, with 23° slopes, while Sur Ridge has $4\text{--}6^\circ$ slopes. Figure 7 shows the limiting angles of downward-going rays as a function of azimuth for each site. The shadow plot for Pioneer Seamount is shown in Figure 8. The corresponding plot for Sur Ridge is similar, except that the Gulf of Alaska is not ensonified. The conclusion is that Pioneer Seamount is the better site, from an acoustics point of view (steep slopes, near-axial peak), for meeting the long- and short-term acoustic thermometry goals of ATOC.

Engineering and Logistics

Swath bathymetry and acoustic backscatter intensity were measured using a 9-kHz side-scan sonar system. Depth resolution was 10 m, with 20-m pixels in the horizontal. (Subsequent 120-kHz high-resolution data collected in August is of only qualitative use because of tow fish navigation problems.) The geologic interpretation of these data, combined with extant data, produced the following description of each site [more detail is in the survey report (Seafloor Surveys, 1993)]. Pioneer Seamount is an old (>20 million years) hot spot volcano on a fragment of an old plate. Underwater volcanoes are usually relatively smooth; a veneer of pelagic sediment at least 1 m thick is expected, with some rock outcrops with a small bathymetric signature. Sur Ridge is sedimentary rock that has been lifted up on the east side and sheared. Sediment on the ridge itself was found to be thin, less than 1 m. As with Pioneer Seamount, there are some rock outcrops with a small bathymetric signature.

The two cable routes are comparable, although there is a degree of additional risk with Pioneer Seamount just because it is so steep. Installation of the source on Pioneer Seamount will unquestionably require more sophisticated equipment to put it in the right spot. The survey company felt that the two cable routes were fairly similar and that the selection should be based on the acoustics and other factors. They identified bottom fishing as the main risk to the cables at both sites and recommended intensive canvassing of local fisherman. Other factors, primarily of an engineering nature, that have been considered are shown in Table 2.



Figure 3. Chart of the Monterey area showing the two candidate sites, Pioneer Seamount and Sur Ridge, and the cable routes.

Bathymetry

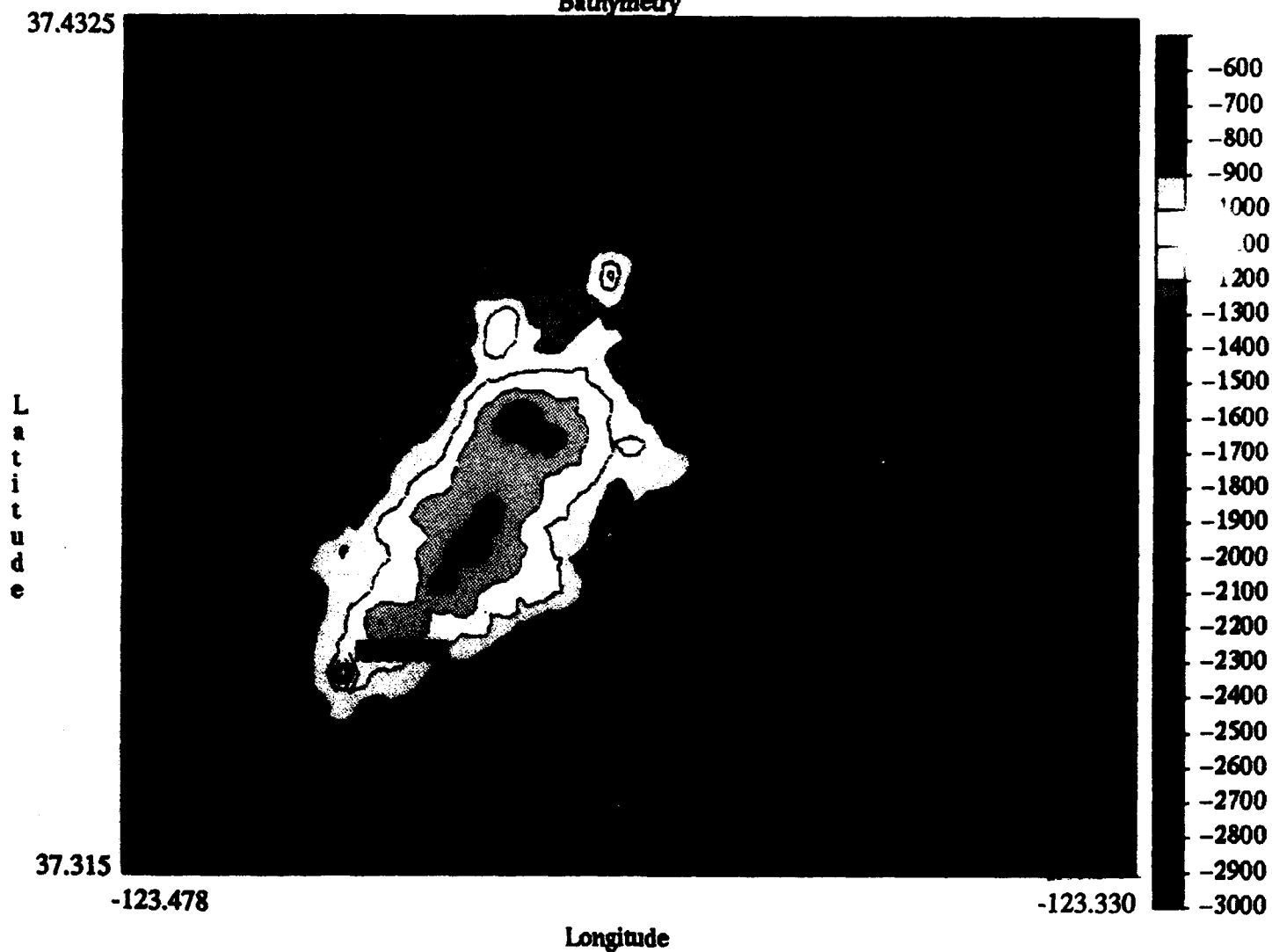


Figure 4. Chart of Pioneer Seamount showing the candidate source site.

Bathymetry

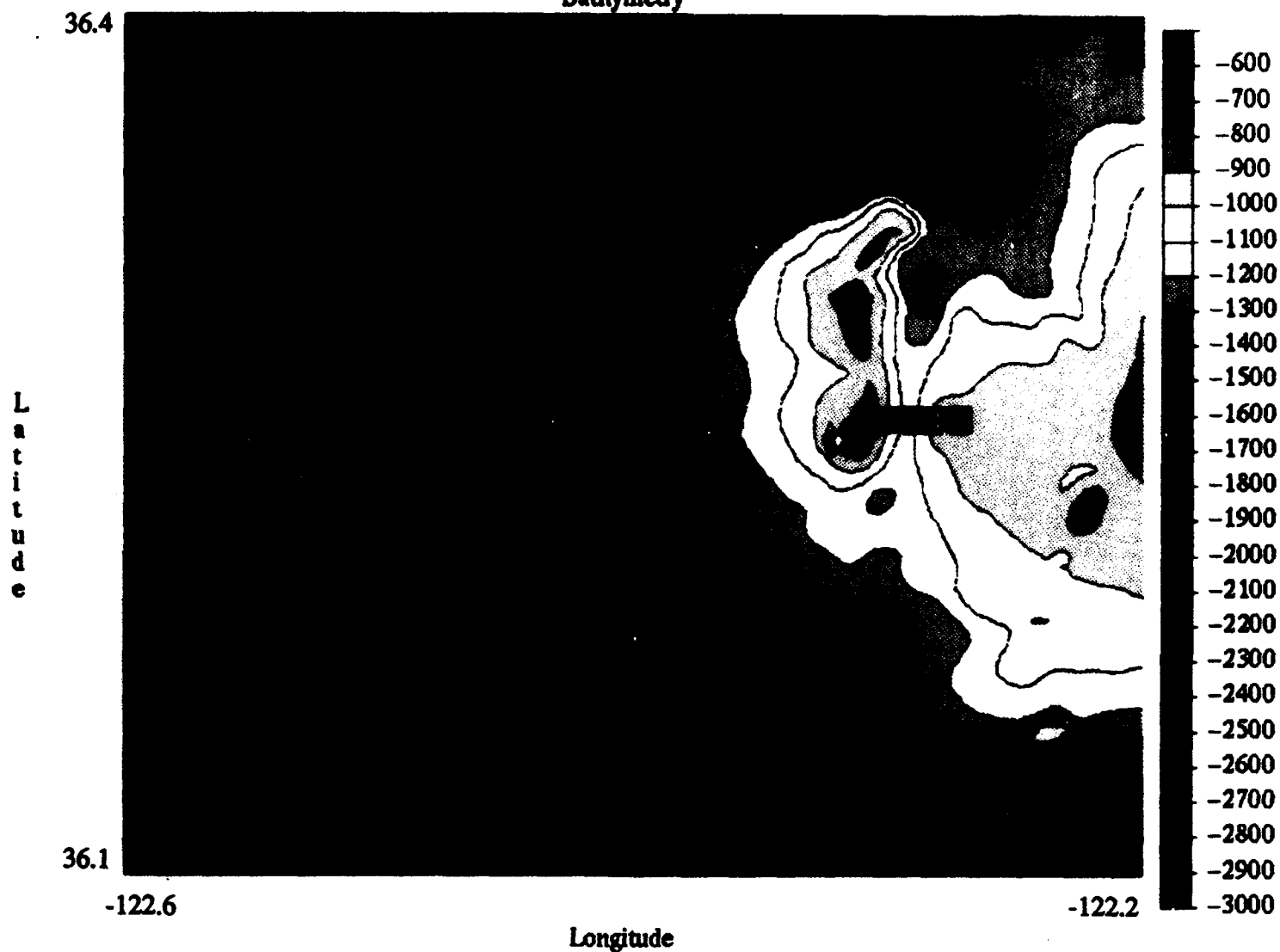


Figure 5. Chart of Sur Ridge showing the candidate source site, as well as the sites of the existing Navy horizontal line array (HLA) and the proposed vertical line array (VLA).

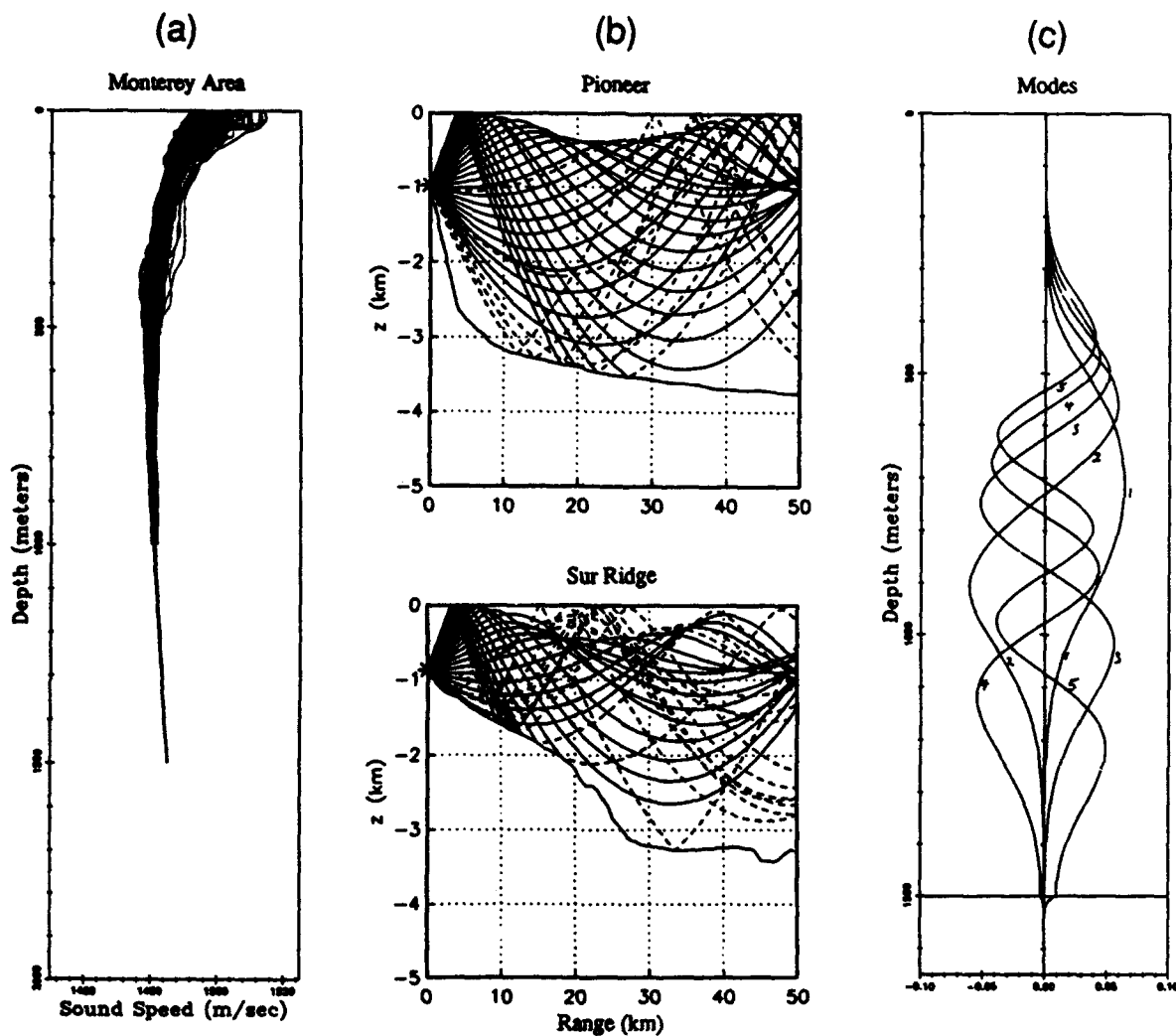


Figure 6. (a) Sound speed profiles for the California sites; (b) for each site, a fan of rays for the Levitus average sound speed profile and bathymetry in the direction of Kauai (-15 to $+15^\circ$ in 1° steps; dashed are bottom interacting); (c) the acoustic normal modes 1-5 (assumes the bottom is at 1500 m).

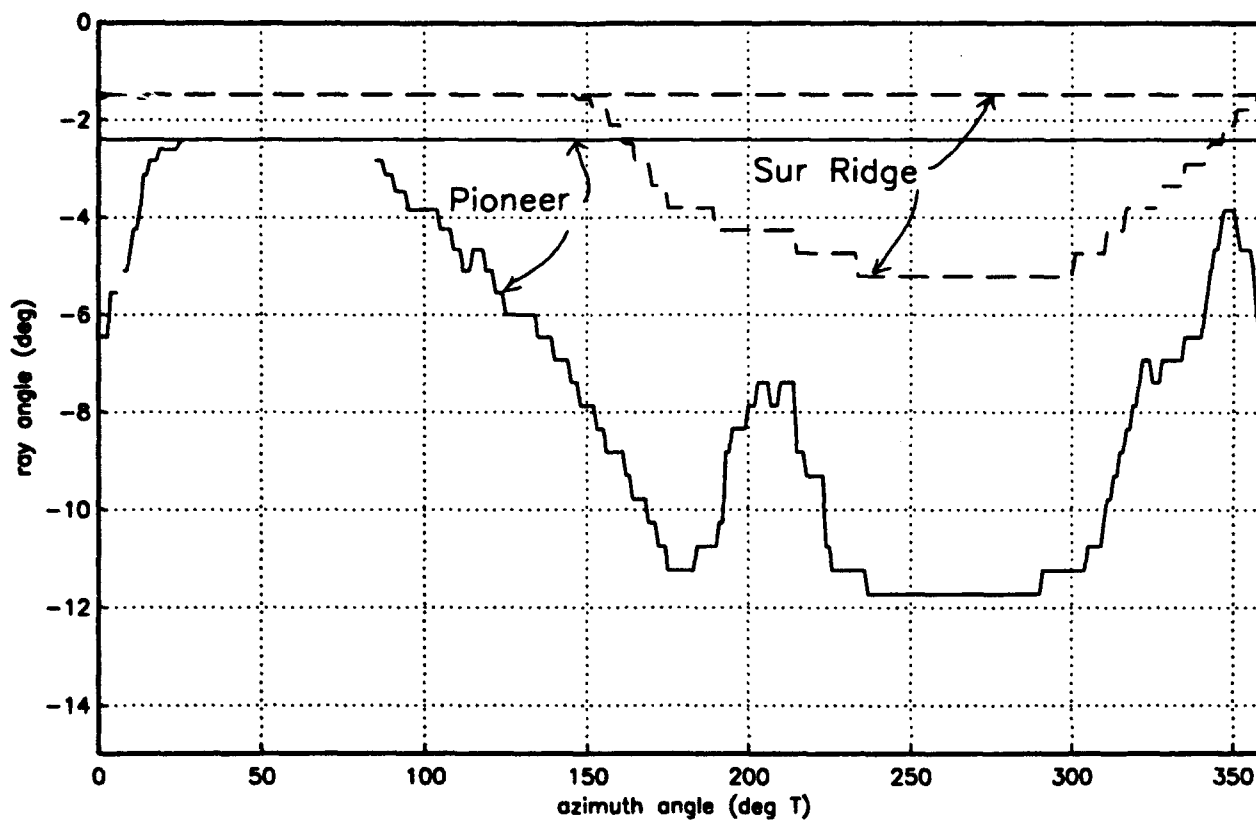


Figure 7. Limiting downward-going-ray angles as a function of azimuth for each site. The minimum angles are also shown (horizontal lines near the top of the figure).

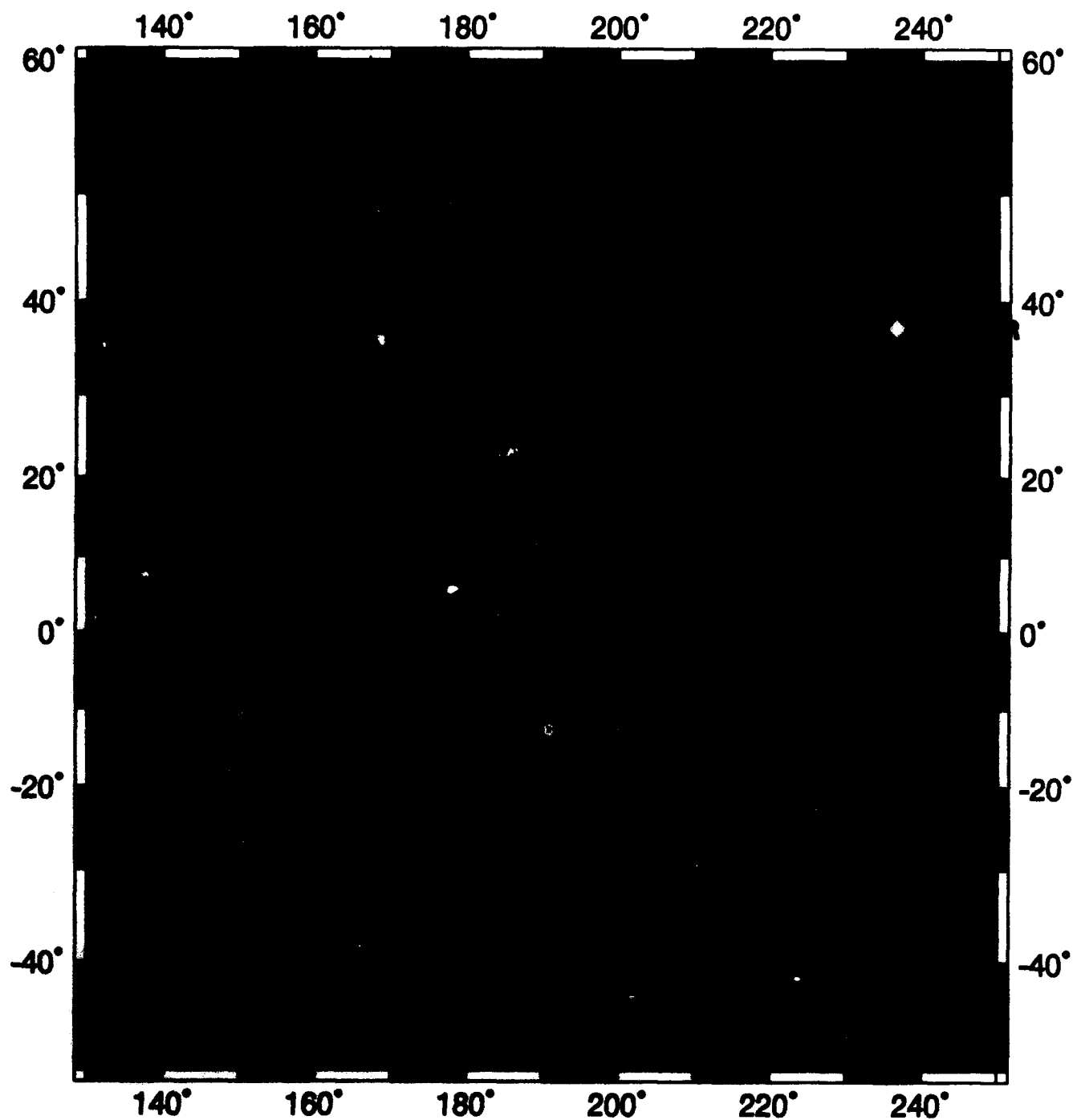


Figure 8. A "shadow" plot for Pioneer Seamount. Depth = 1000 m.

Table 2. Comparison of potential ATOC source sites, Pioneer Seamount and Sur Ridge.

	Pioneer Seamount	Sur Ridge
Latitude	37° 20.555' N	36° 18.109' N
Longitude	122° 26.698' W	122° 19.265' W
Nominal depth	980 m	880 m
ACOUSTICS		
Limiting surface RR ray		8.8°
Limiting bottom RSR ray (3500 m)		12.1°
Azimuthal aperture		
-4° ray	264°	128°
-5° ray	235°	66
-8° ray	153°	0°
-11° ray	89°	0°
Local bottom description	basalt with thin sediment cover, some rock outcrops	sedimentary rock with thin sediment cover, some rock outcrops
ENGINEERING and LOGISTICS		
Distance to shore (n.mi.)	46	26
Rock traverses; depth, length (m)	0-40, 2	0-30, 1 100-110, 1 200-220, 1
Armor at shore end (n.mi.)	3	3
Visual inspections		no good data yet
Distance to 5 m depth (n.mi.)	0.1	0.1
10 m	0.3	0.2
20 m	0.6	0.6
50 m	3.4	1.7
100 m	15.4	6.2
200 m	19.2	9.2
Shore landing		equal
Shore facility	Air Force space, Pillar Point	old Navy facility
Proximity to civilization	45 min to SFO	1 h to Monterey 3 h to SFO

Table 2, cont.

	Pioneer Seamount	Sur Ridge
Fishing threat	primary hazard in both cases; equal risk; relatively small (60 ft) boats cross both paths	
Source installation	requires transponder net	requires a marker transponder
allowable footprint	40 m parallel to contours 5 m depth	80 m parallel to contours 10 m depth
difficulty	more difficult	less difficult
Installation schedule		equal
Permit	outside sanctuary	inside sanctuary
Long-term operating costs		equal
Estimated life		equal
Source and cable repairs, ease of		equal
Earthquake/landslide/slumping risk		equal
Wind, typical (knots)	15-25	10-20

How difficult will it be to install a source at either site? In both cases, the best deployment scenario would be to put the source in first (with the cable attached) and then string the cable to shore. The next best alternative (assuming the cable must be laid first because of the cable ship's schedule) would be to install the source with a long pigtail. This would let us position the source without having to worry about the shore cable. Then in a separate operation the pigtail and the shore cable can be spliced together some distance from the source so as not to disturb it. The last possibility is to lay the shore cable directly to the site, raise the cable, attach the source, and lower it into place. In this scenario, the weight and "free will" of the shore cable will make it difficult to position the source exactly. Furthermore, the cable may move around on the bottom; if it moves over sediment, there is no problem, but if there are rocks, the cable could be damaged.

At Sur Ridge, the plan would be to bring the cable around the ridge and up the western slope (Figure 3), thereby avoiding the steeper slopes on the east side. This would also leave "extra" cable on the seafloor for future contingencies. Any of the scenarios described above would work at Sur Ridge. Also, given the topography, the permissible "footprint" is rather large and a transponder navigation net is not needed. The permissible error in location along contours is on the order of 50-100 m and in depth it is about 10 m. By monitoring depth carefully during deployment, we should be able to get the source close enough to the desired position.

At Pioneer Seamount, only the first two scenarios could be used. A primary concern is to be sure there are no cable suspensions (cable strumming due to tidal currents could lead to abrasion and failure at the suspension points). The data we have indicate that there are no steep ravines where this might occur. The tolerances on the source location are tighter: 40 m parallel to the contour and 5 m in depth. Given the topography of the seamount, we will most likely have to deploy a transponder navigation net to help guide the source into position.

Other Factors

Several other factors enter into the site selection decision. Both the Monterey Bay Aquarium Research Institute and the Naval Postgraduate School expect to use the Sur Ridge horizontal line array (HLA, the decommissioned Navy array) as part of a local acoustic observatory. It has been decided to place the ATOC vertical line array (VLA) about 5 n.mi. west of the HLA (there is not enough cable/money to put the VLA off Pioneer Seamount) to form a crude 3-D array. Bottom interaction is less of a problem with the VLA because it will be placed in 1800 m of water just adjacent to where the slope steepens to the west (in the direction of the Kauai source). There may be some small cost savings if both the VLA and the source cables are terminated at the Pt. Sur Naval Facility. There is some intuition that concentrating resources (at Sur Ridge) might be a good idea. The main reason for adding the short vertical array to the source was to be sure that truly reciprocal data could be obtained; it also provides partial redundancy to the VLA.

The remaining two connected factors are the permit and marine mammal issues (I now draw on conversations with A. Bowles (Hubbs - Sea World), C. Clark (Cornell University), and D. Snyder (ATOC Project Office)). Permits are required from the Monterey Bay National Marine Sanctuary for physically installing the cable and source on the bottom. The California State Lands Commission regulates the strip from the mean high water mark (MHW) to 3 n.mi. offshore, and the California State Coastal Commission regulates the strip of land from the MHW to 3 miles inland. NMFS regulates anything having to do with marine mammals, in this case possibly "harassing" mammals by putting sound in the water. We think the main bottleneck is the NMFS permit; all permits for the two California sites are for the most part site-independent.

NMFS will require a permit for a source off California, and it has been decided that the best course is to obtain a research permit, which requires a full research program. The details of this research program are still being worked on. The program will by necessity focus on the requirement to track marine mammals, both whales and smaller animals like elephant seals. The standard method is visual tracking using aircraft and observers on land. New satellite tracking tags have been developed and will be used. And acoustic tracking will be used. One goal of the work will be to "verify" the acoustic tracking results with the conventional visual tracking results.

The advantages and disadvantages of each site from the perspective of marine mammal research are as follows (I take this almost verbatim from conversations/messages from A. Bowles and C. Clark):

Pioneer Seamount

Advantages:

- Close to the Farellons (30 n.mi.), where whales are tagged for satellite tracking
- Outside the Monterey Bay and Farellons Sanctuaries
- Might be possible to track whales in the larger area between Pioneer and Sur Ridge, thus obtaining a larger sample. (The Navy HLA is oriented along 350°T-170°T and the bearing from Sur Ridge to Pioneer Seamount is 320°T, so useful azimuth resolution from the HLA is possible.)

Disadvantages:

- Farther offshore than Sur Ridge, so increased cost of aerial surveys and no possibility of making observations from shore
- Far (83 n.mi.) from the cabled VLA and HLA.

Sur Ridge

Advantages:

- Zone of influence close to shore
- Near migratory pathway of gray whales (for playback experiments)
- VLA and HLA close to the source, which may simplify tracking
- Close to shore for aircraft
- Close to sites used in historical experiments on gray whale response to noise.

Disadvantages:

- Inside Monterey Bay National Marine sanctuary
- More distant from whale tagging site.

The Decision

The final decision made by the ATOC Executive Committee was in favor of the Sur Ridge site. I quote from their statement

The Pioneer Seamount option is better acoustically and is feasible from an engineering viewpoint, but it does not meet the marine mammal monitoring requirements. Marine mammal research issues are now driving site selection to provide acoustic receiver assets nearby the source, i.e., at the Sur Ridge site. The marine mammal permit is still a major issue, but concern is not over obtaining the permit... as much as how affordably ATOC can execute the necessary marine mammal studies.... Given the circumstances, Point Sur is the only option which provides the necessary assets to conduct marine mammal research for a California source.

4. SUMMARY

The Sur Ridge site has been chosen because the necessary marine mammal research can be conducted there for less cost than at the Pioneer Seamount site. The short-term realities of permits and cost have required a choice that is suboptimal from a long-term ATOC acoustics point of view. This may be an example of what we will face in selecting other ATOC source sites. While it is hoped that the marine mammal issues will be largely solved, it will probably always be necessary to balance good acoustic site characteristics against cost and engineering/logistics considerations.

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